Using Graphene as Transparent Electrodes for OLED Lighting

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The Search for New Transparent Conductive Electrodes (TCEs)

	Sheet resistance	Optical Transmission	Ease of Customisation	Haze	Ease of patterning	Thinness	Stability	Flexibility	Reflection	Low Cost
ITO-on-Glass	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓	✓✓✓✓	✓	✓	✓
ITO-on-PET	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓	✓✓✓✓	✓✓	✓	✓
Silver Nanowires	✓✓✓✓	✓✓✓✓	✓✓✓	✓	✓✓✓	✓✓✓✓	✓	✓✓✓✓✓	✓✓✓✓	✓✓✓
Graphene	✓	✓✓✓✓✓	✓✓	✓✓✓✓✓	✓✓✓	✓✓✓✓✓	✓✓	✓✓✓✓✓	✓✓✓✓✓	✓
Carbon Nanotubes	✓✓✓	✓✓✓✓	✓✓✓	✓✓✓✓✓	✓✓✓	✓✓✓	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	✓✓
PDOT:PSS	✓	✓✓✓	✓✓✓	✓	✓✓✓✓	✓✓	✓	✓✓✓✓✓	✓✓✓	✓✓✓✓✓
Micro Fine Wire	✓✓✓✓	✓	✓✓✓✓✓	✓✓	✓✓✓✓✓	✓	✓✓	✓✓✓✓✓	✓✓✓	✓✓✓✓✓
Metal Mesh (emboss)	✓✓✓✓✓	✓✓✓	✓	✓✓	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓	✓✓✓✓✓
Metal Mesh (direct print)	✓✓✓✓✓	✓	✓	✓✓	✓✓✓✓✓	✓✓	✓✓	✓✓✓✓	✓✓✓	✓✓✓✓✓
Metal mesh (etching)	✓✓✓✓✓	✓✓✓	✓✓	✓✓	✓✓✓✓✓	✓✓	✓✓	✓✓✓✓	✓✓✓	✓✓✓✓✓
Other nanotechnology	✓✓✓✓✓	✓✓✓✓	✓✓✓✓✓	✓✓	✓✓✓✓✓	✓✓✓✓	✓✓✓	✓✓✓✓✓	✓✓	✓✓✓

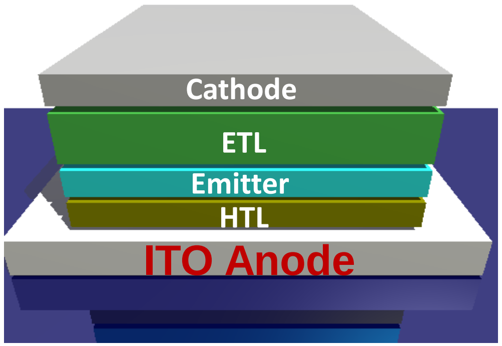
Excellent	✓✓✓✓✓
Good	✓✓✓✓
Moderate	✓✓✓
Moderate-to-Poor	✓✓
Poor	✓

IDTechEx, 2013

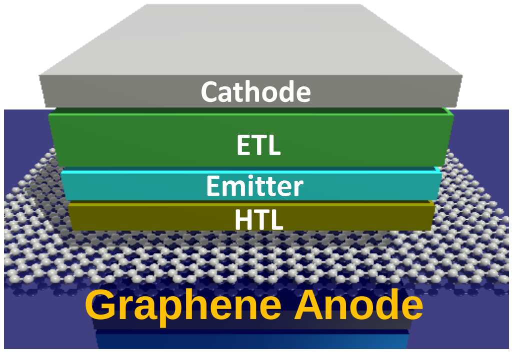
Motivation:

- Reduce cost
- New features: highly flexible, stretchable…
- More performance: higher conductivity, better charge injection, better light extraction…

Advantages of Graphene TCEs



Conventional OLED on ITO/Glass

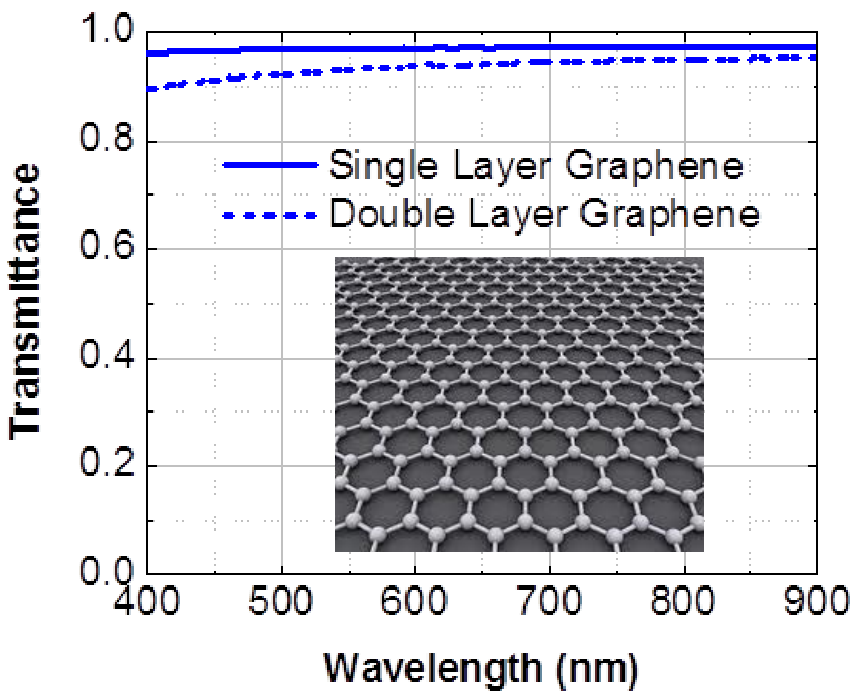


Low cost flexible OLED on Graphene/Plastic

	Graphene Transparent Electrode
Mechanic Flexibility	**The most flexible** transparent electrode, bending radius **<1mm**, enable rollable and foldable applications
Light Extraction	**Better light extraction**, high transmission, very low reflection, no light trapping in the electrode
Stability	**Stable** and compatible with organics. Very inert material, no oxidation or reaction with organics
Substrate	**Same performance** on all substrates
Cost	**Low cost** graphene process are being developed. Huge cost reduction potential using large area roll to roll processes.

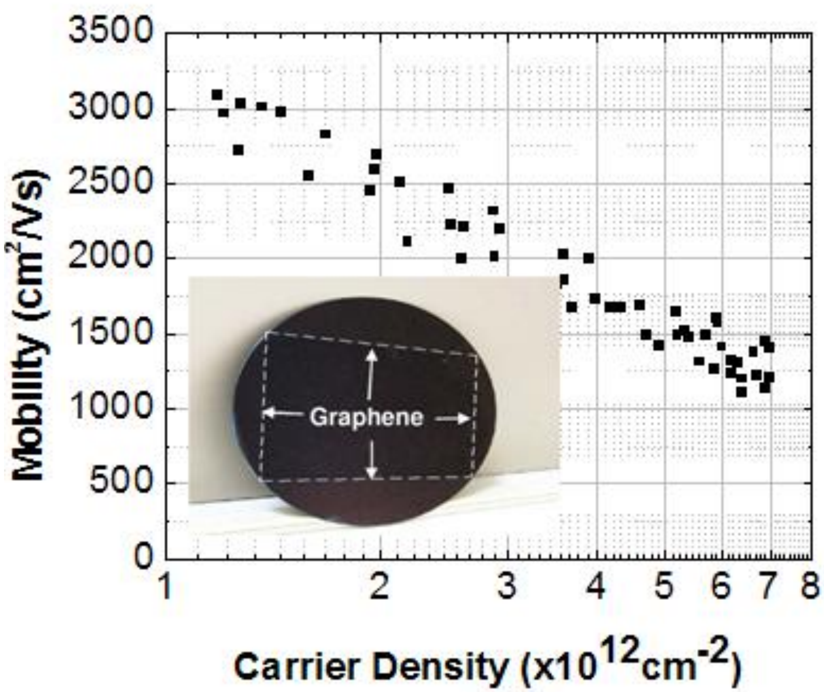
Challenges for Graphene TCE

Keep High Transmittance



- High transparency >97%
- Decreases ~3% for each additional layer

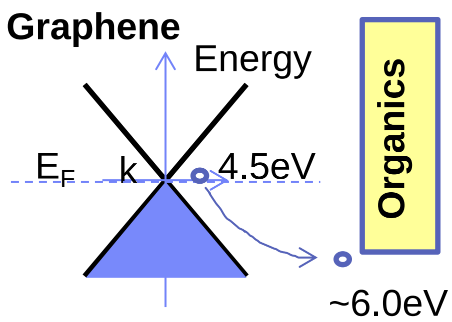
Improve Conductivity and Charge Injection

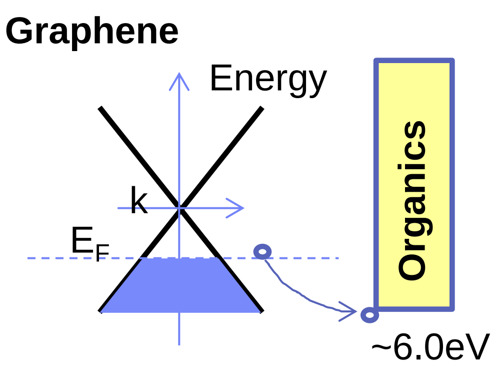


- High carrier mobility >150,000cm^2/Vs in theory, but measured is ~3,000cm^2/Vs, R_s>1kΩ/ □
- Work function W_F= 4.5eV, too low as Anode for hole injection

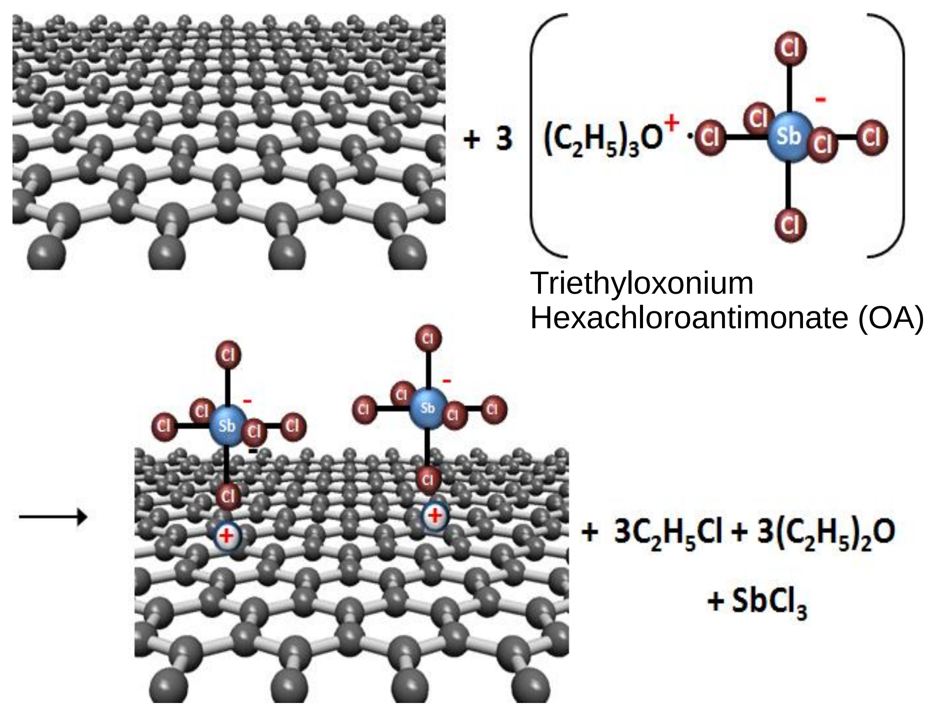
Doping Graphene to Increase Conductivity and Work Function

Energy Level Diagram





Doping Process

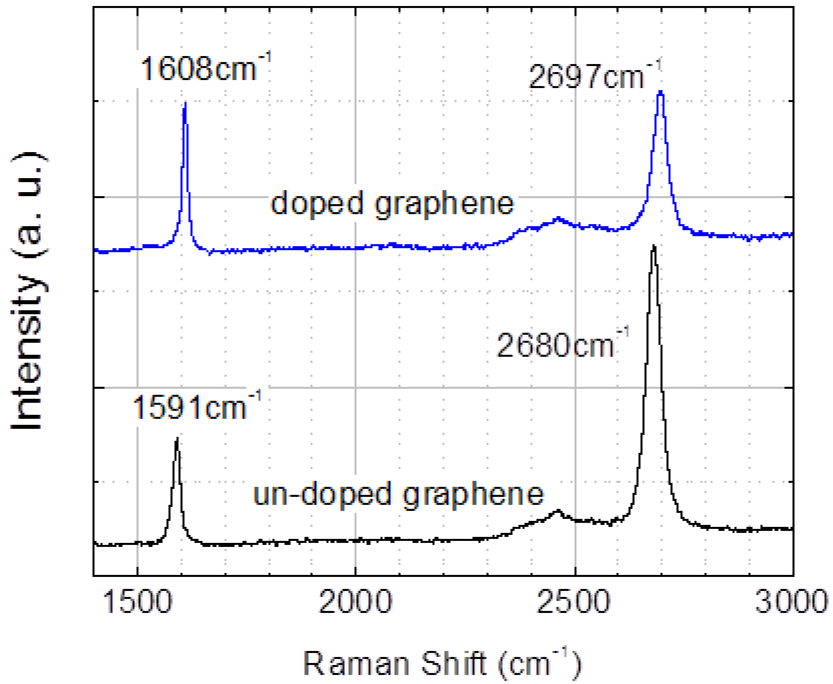


- Increases graphene free carrier density for lower resistance
- Increases graphene work function for hole injection

- Non-volatile charge-transfer complex
- Longer doping lifetime

Doping Graphene to Increase Conductivity and Work Function

Raman Spectroscopy



Work function (W_F) Shift

Raman Shift $= \triangle W_F \times 42\ cm^{-1}eV^{-1}$

Work Function and Carrier Density

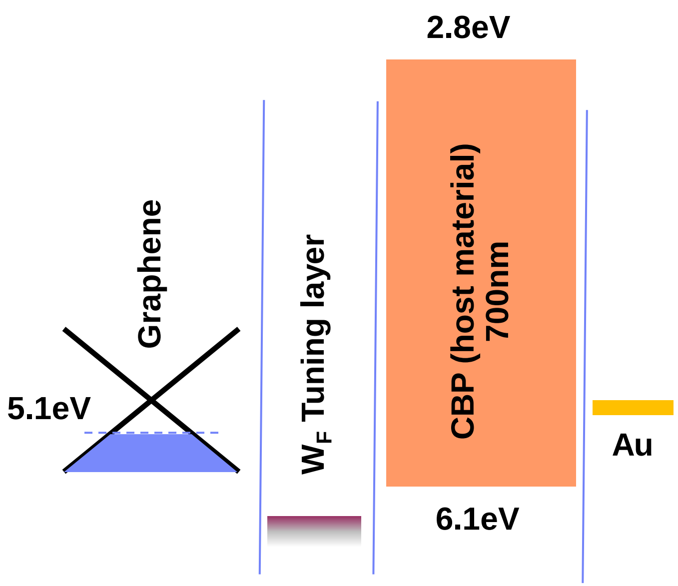
Material	W_F (eV)	Carrier density
ITO	4.78	
Undoped Graphene	4.70	~5×10^{11} cm^{-2}
P-doped Graphene	**5.10**	**~3×10^{13} cm^{-2}**

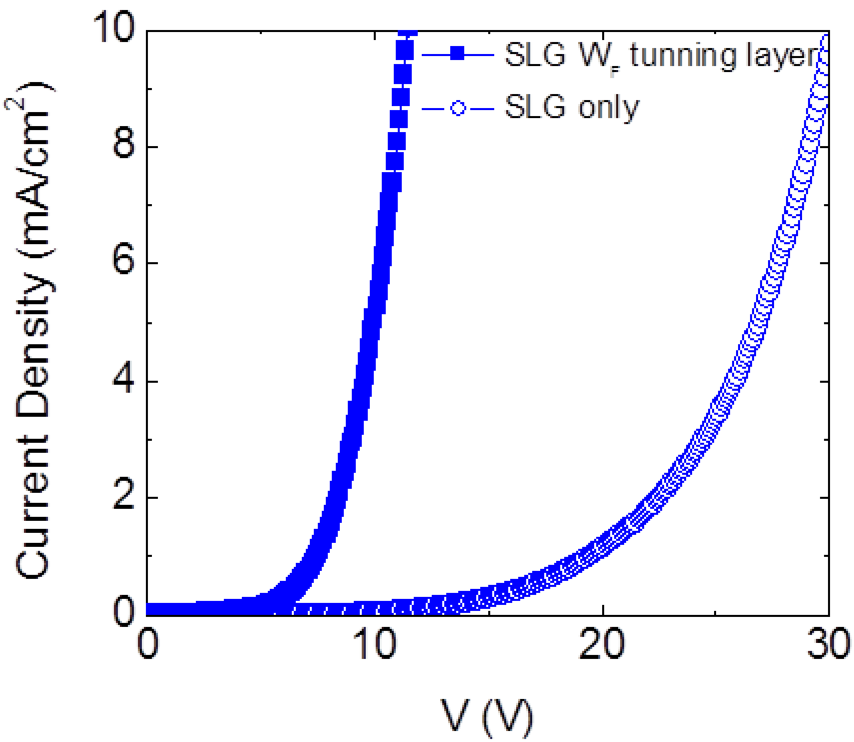
- Sheet Resistance is reduced from >1kΩ/□ to 100~200Ω/□ (97% transmittance).

Hole Injection Using High W_F Interface Layer

Direct Hole Injection Into CBP

Much Reduced Energy Barrier

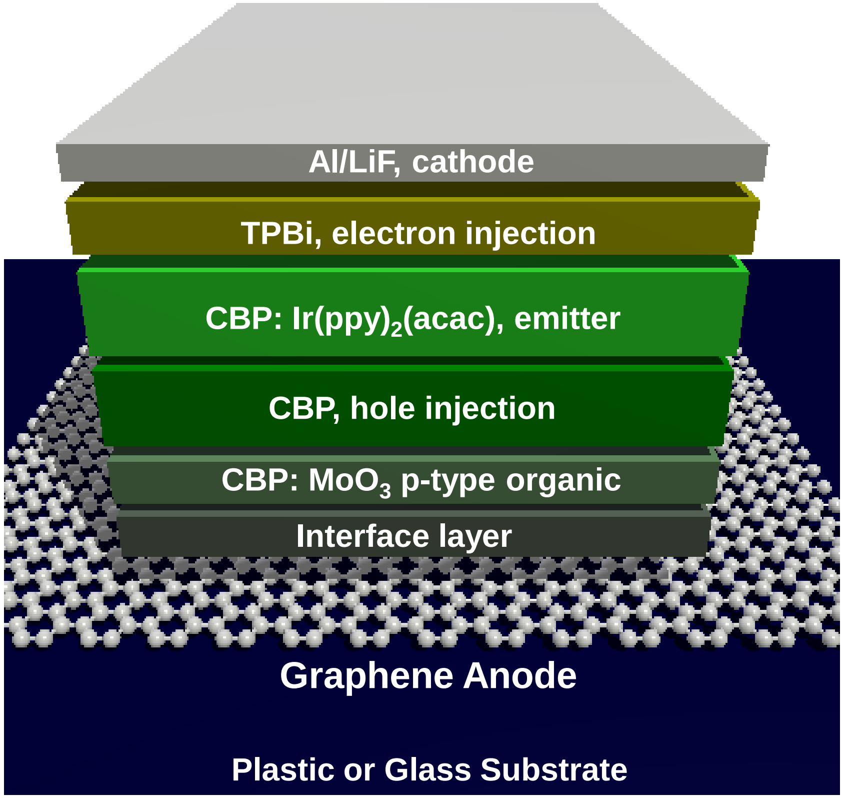




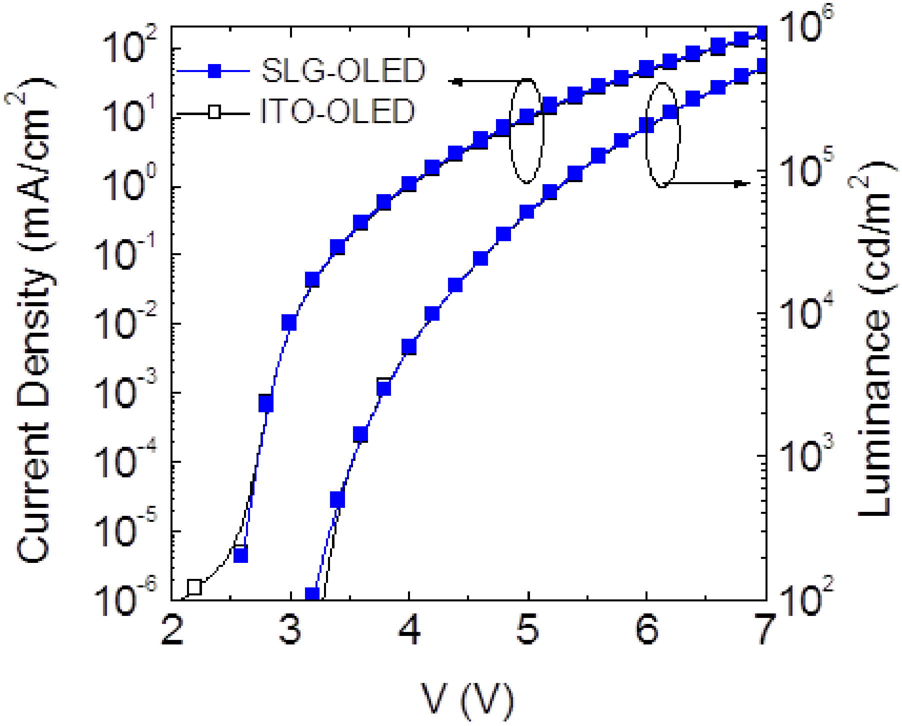
- Direct and Efficient hole injection from Graphene to emitter host material CBP

Green OLED on Graphene

Green OLED on Graphene Structure

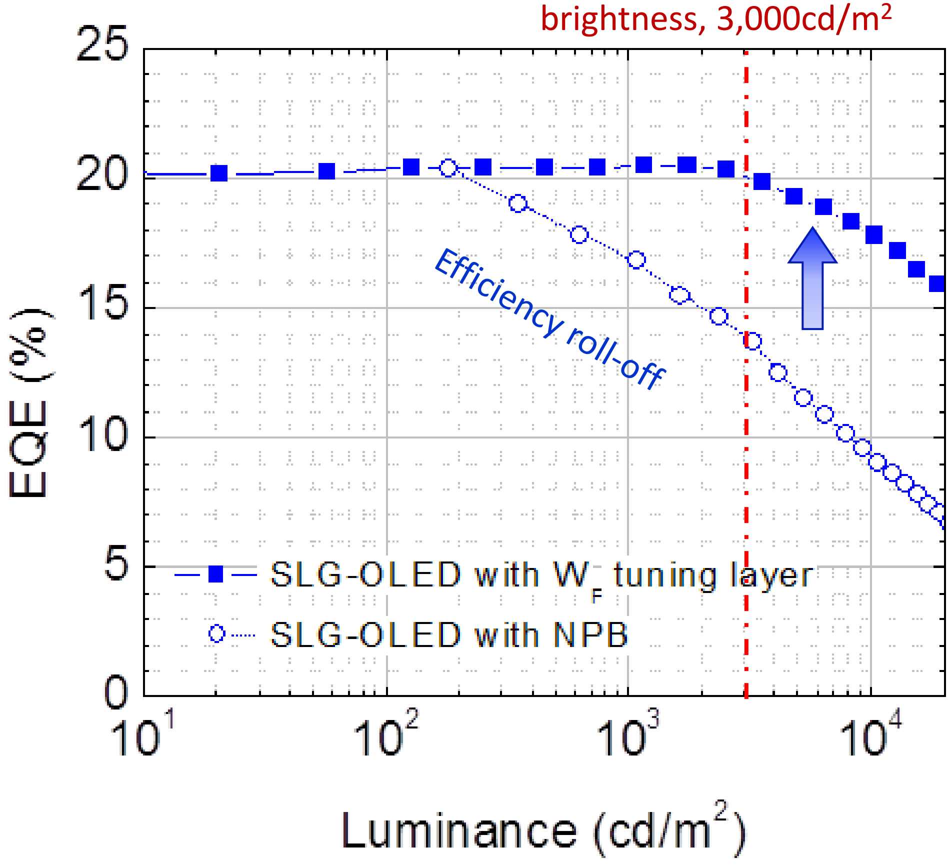


Equivalent Performance as on ITO

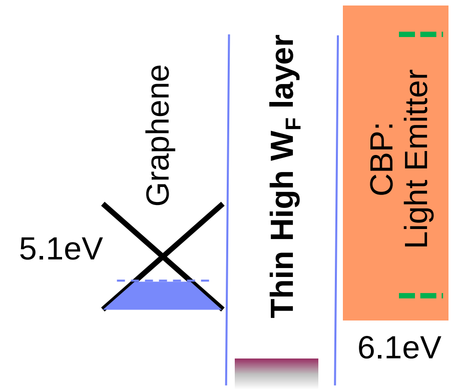


- OLED on single layer graphene (SLG) on plastic exhibits similar I-V and L-V as same device on ITO/glass

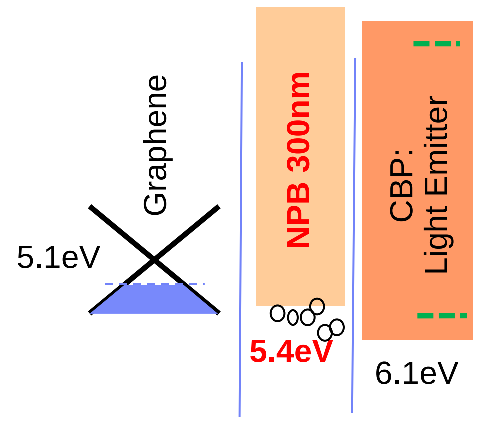
Enhance Light Intensity for General Lighting Requirement



SLG-OLED with high W_F injection layer



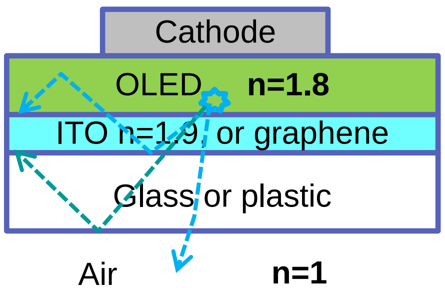
SLG-OLED with conventional NPB layer



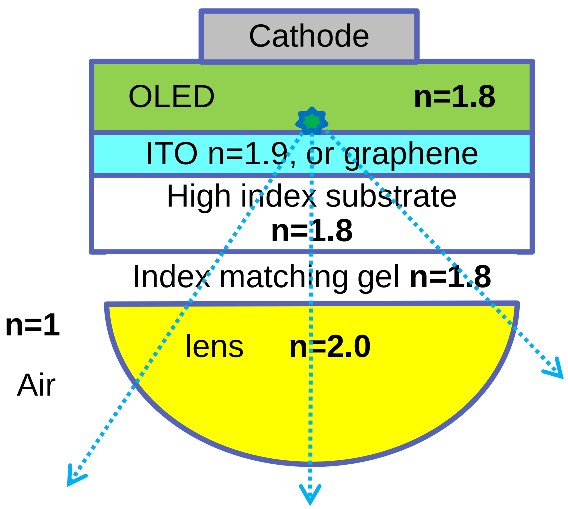
- OLED output luminance is enhanced using high work function injection layer

Enhance Light Out-coupling Efficiency

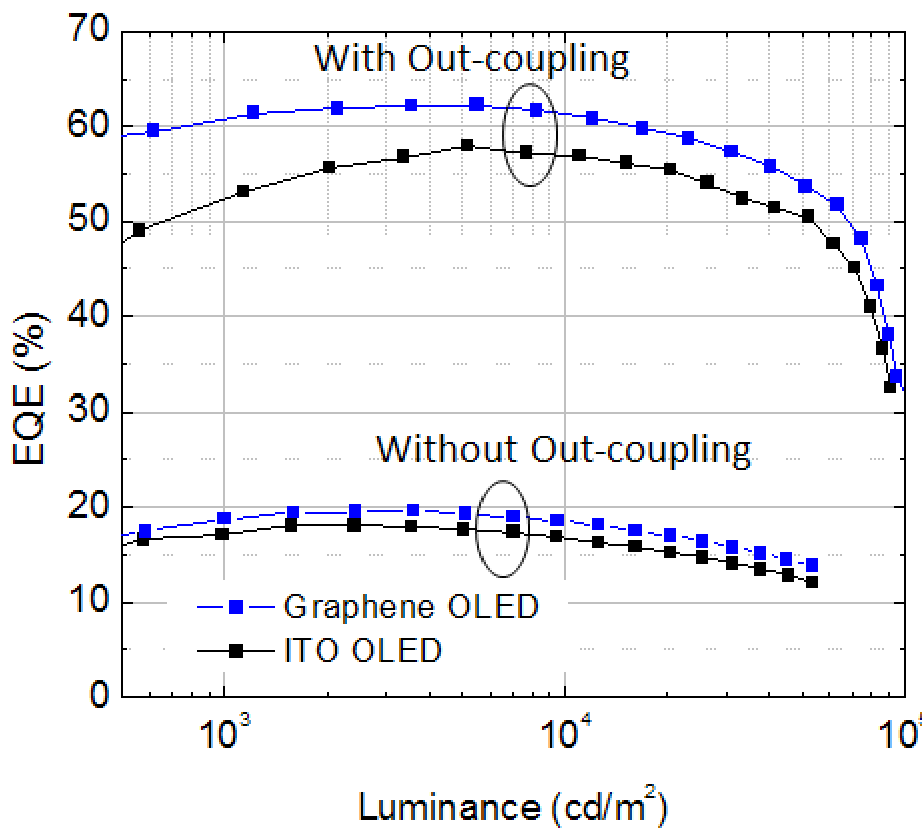
No Lens



With Lens



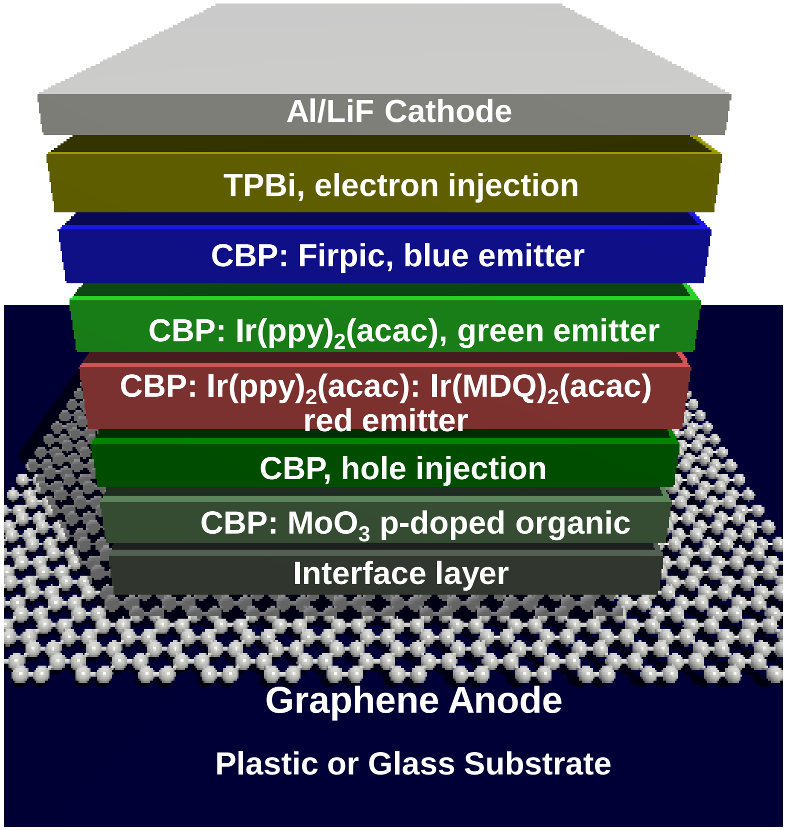
EQE > 60% at 10,000cd/m² (Green)



- EQE>60% is achieved at 10,000cd/m^2 with enhanced light out-coupling
- More light is coupled out of the Graphene electrode with lens

White OLEDs (WOLEDs) on Graphene

WOLED Structure on Graphene

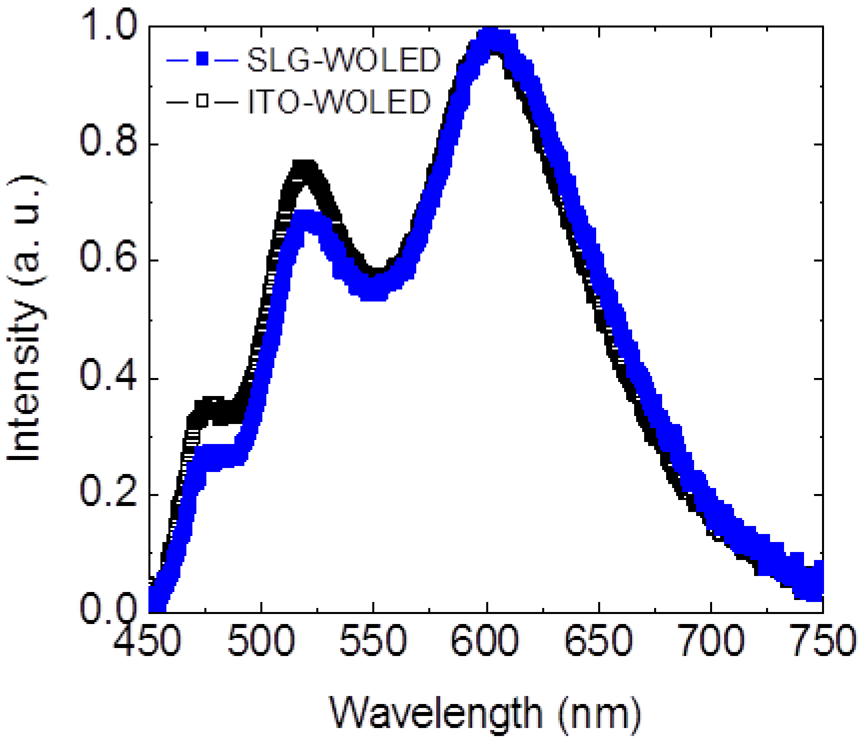


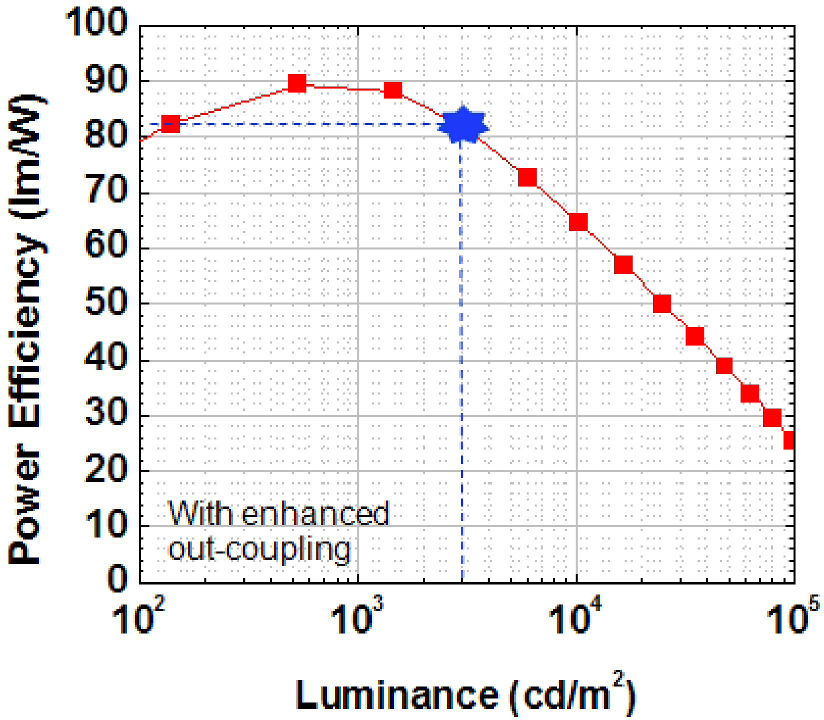
Demo of Graphene-WOLED

Graphene-WOLED with Lighting Performance

Color Rendering Index (CRI) =85

PE > 80lm/W at 3,000cd/m²





- A demonstration of WOLEDs on alternative TCE with lighting performance

Li, *et al.*, Nature Comm., Aug 2013

Rapid Progress of TCEs for OLEDs

TCE Materials	Conductivity/ Transparency (at 550 nm)	Demonstrated OLED Performance	Light Extraction	Reliability	Mechanical Flexibility
ITO	10Ω/sq at 90%	>100lm/W	Light trapping in ITO	Good	poor
CNTs	500Ω/sq at 85%	10cd/A at 1000cd/m^2	Medium	Excellent	Flexible /Stretchable
Metal Nanowires	9.7Ω/sq at 89% 30Ω/sq at 93%	54lm/W similar to ITO control device	High Angle Uniformity	Good	Flexible /Stretchable
Conductive Polymer	39Ω/sq at 80%	12% EQE similar to ITO device	High	Medium	Flexible
Graphene	125Ω/sq at 97% 30Ω/sq at 90%	103 lm/W for green 80lm/W for white	High	Excellent	Most flexible /Stretchable

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Summary

- White OLED on Graphene achieved lighting performance
  - Improved conductivity for better charge distribution on Graphene
  - Improved charge injection from Graphene to organics for lower turn on voltage and high brightness and efficiency

- Further challenges for Graphene electrodes
  - Improve conductivity and transparency, large area lighting panels
  - Roll to roll process to increase throughput and reduce cost
  - Optimize for light extraction
  - …